

The MUonE experiment: a novel way to measure the hadronic contribution to the muon $g - 2$

Eugenia Spedicato on behalf of the MUonE
collaboration

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Scattering for $g-2$ " under the program PRIN 2022



ICHEP 2024, Prague

ANOMALOUS MAGNETIC MOMENT OF THE MUON

$\vec{M}_l = g_l \frac{e}{2m_l} \vec{S}$ \longrightarrow Dirac prediction $g_l = 2$ \longrightarrow Quantum corrections give the *anomaly*:

$$a_l = \frac{g_l - 2}{2}$$

Experimental average **FERMILAB+BNL**

P. B. Aguillard et al., (2023) [PhysRevLett.131.161802](#)

VS

Theoretical *reference value (WP)*

T. Aoyama et al., (2020) [Phys. Rept. 887 \(2020\) 1-166](#)

but...

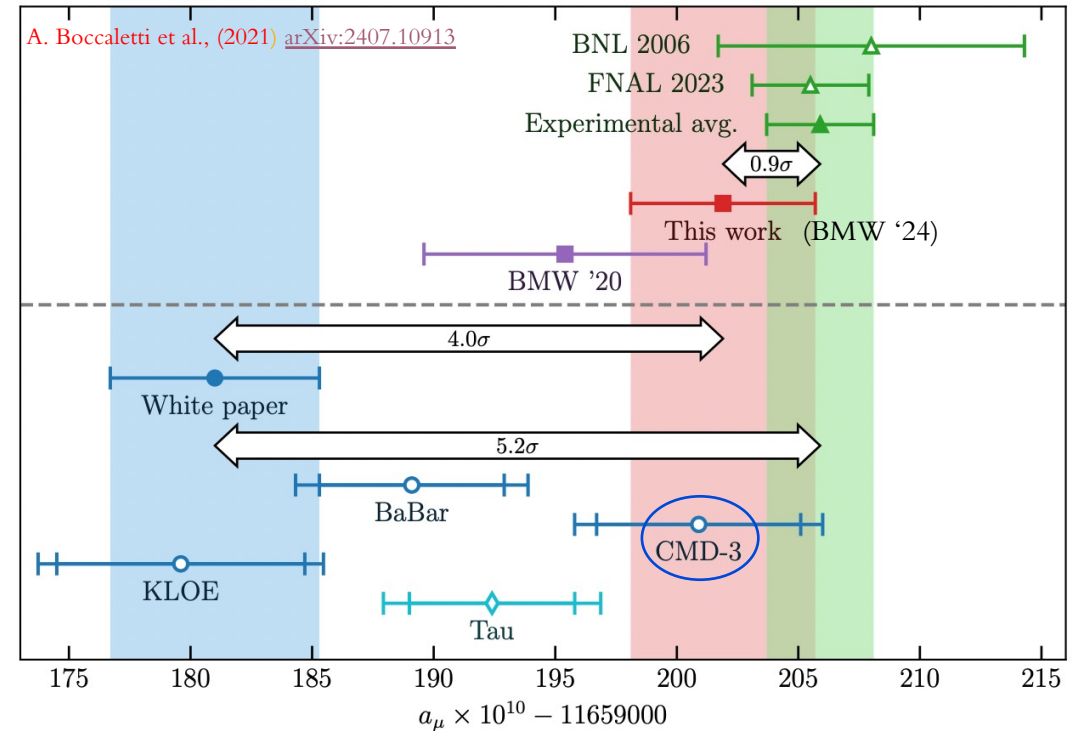
Most precise **LQCD** result

A. Boccaletti et al., (2024) [arXiv:2407.10913](#)

New result from $e^+ - e^- \rightarrow \text{had}$ cross section with **CMD-3** data

F. V. Ignatov et al., (2023) [Phys. Rev. D 109, 112002](#)

Are those *discrepancies* still real? Hint of *new physics*?

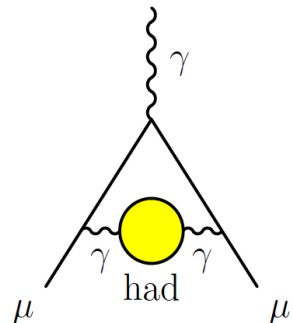


2

1. Reduce the *experimental* error \longrightarrow Fermilab g-2 goal (0.54 ppm (BNL) \longrightarrow 0.20 ppm \longrightarrow 0.14 ppm) *goal*

2. Improve *theoretical* precision \longrightarrow Dominant contribution: LO hadronic vacuum polarization term

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EWK} + a_\mu^{had} \longrightarrow a_\mu^{HLO} \longrightarrow 0.6\%$$



MUONE PROPOSAL

Independent estimate of a_μ^{HLO} through innovative method:

C.M. Carloni Calame, et al. [Phys.Lett.B746\(2015\)325](#)

$$a_\mu^{HLO} = \frac{\alpha}{\pi} \int_0^1 dx (1-x) \Delta\alpha_{had}[t(x)] \xrightarrow{\text{Smooth function}} \text{Space-like}$$

B. E. Lautrup et al., [Phys. Rept. 3 \(1972\) 193](#)

Proposed process to measure $\Delta\alpha_{had}$: **elastic scattering**

G. Abbiendi et al., [Eur.Phys.J.C77\(2017\)139](#)

$$\mu (160\text{GeV}) + e^- (\text{rest}) \rightarrow \mu + e^-$$

M2 muon beam at CERN SPS

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt} \left| \frac{1}{1 - \Delta\alpha(t)} \right|^2 \xrightarrow{\text{Template fit}} \Delta\alpha_{had}(t) \xrightarrow{\text{Master integral}} a_\mu^{HLO}$$

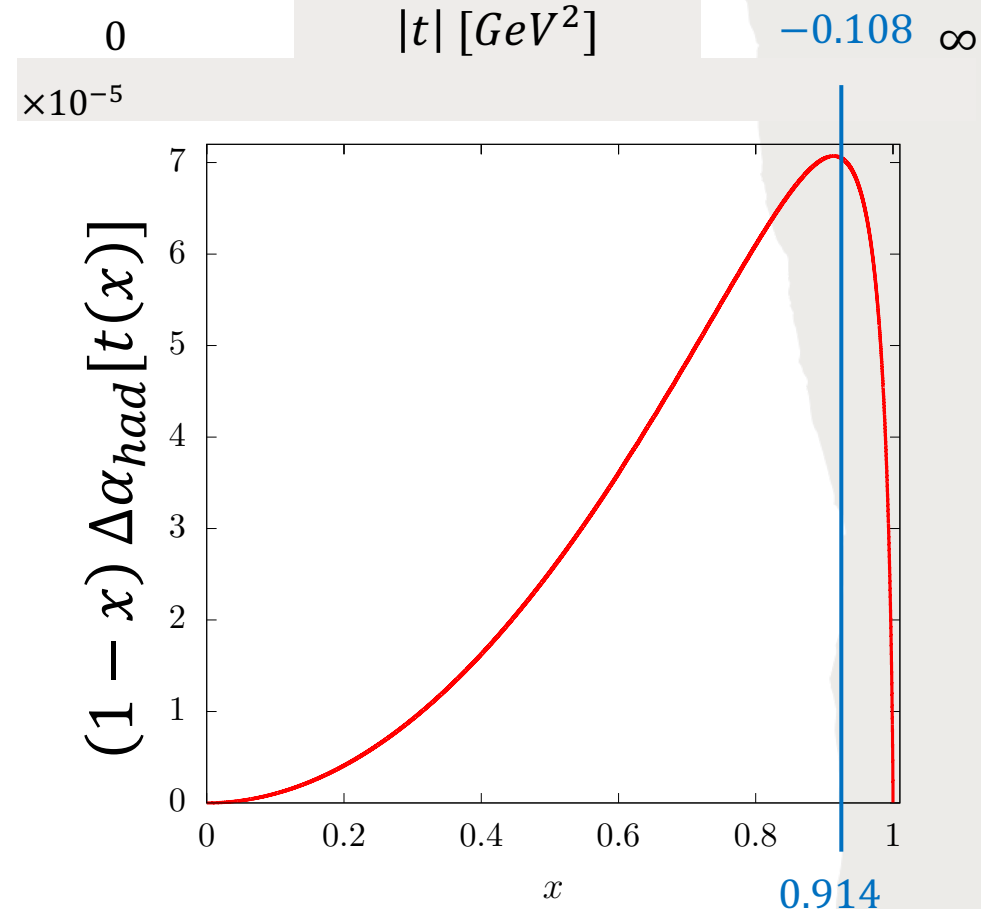
$$\Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t)$$

$$\frac{d\sigma_{el}}{dt} \xleftrightarrow{\text{Simple kinematics relations } (t \leftrightarrow \theta_l)} \frac{d\sigma_{el}}{d\theta_l}$$

Measuring the **leptons scattering angles**

Required precision on $a_\mu^{HLO} < 1\%$ implies a relative precision of $\sim 10^{-5}$ on the shape of the elastic differential cross section

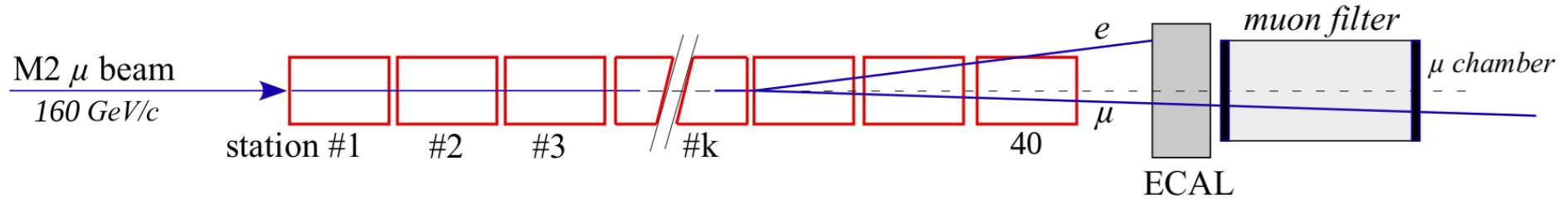
THEORETICAL



Great challenge in terms of required **precision!**

EXPERIMENTAL APPARATUS

40 tracking stations + Electromagnetic calorimeter + Muon chambers



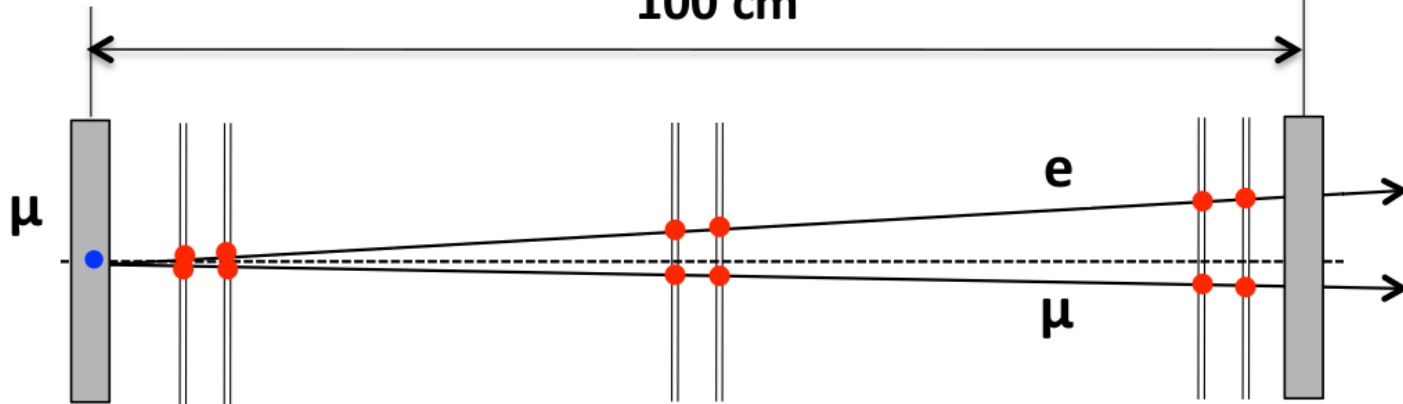
Each *tracking station* behaves as an independent *detector*

1 beryllium or carbon target (1.5 cm)

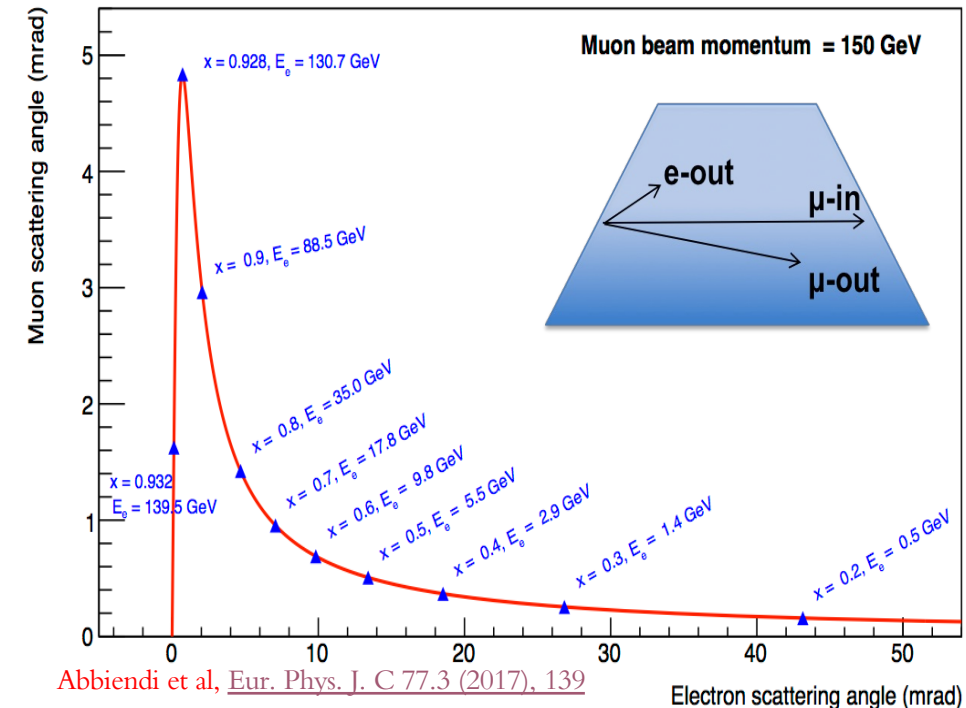
6 silicon strip modules (CMS 2S modules)

Modular layout to achieve the necessary interaction rate *minimizing* systematic effects (e.g. MCS)

~ 100 cm



Letter of Intent: The MUonE Project, [SPSC-I-252](#)

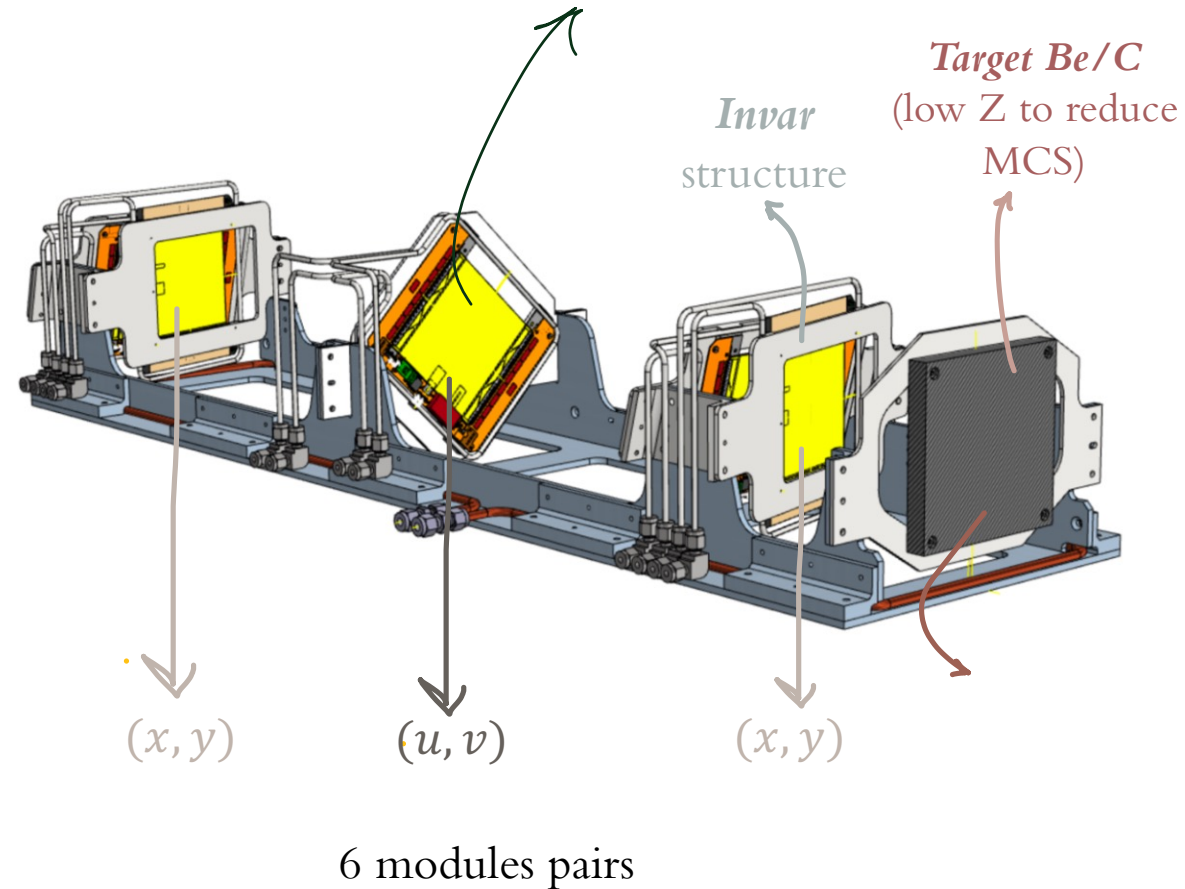


Abbiendi et al, *Eur. Phys. J. C* 77.3 (2017), 139

The experimental apparatus: *tracker and ECAL*

Thickness: $2 \times 320 \mu\text{m}$
Pitch: $90 \mu\text{m}$ ($\sigma_x \sim 26 \mu\text{m}$)
Readout rate: 40 MHz
Active area: $10 \times 10 \text{ cm}^2$

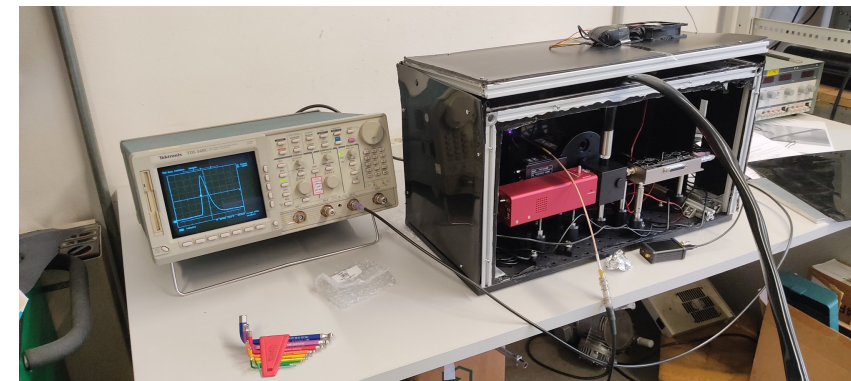
1 CMS 2S module = 2 coupled *silicon strip sensors* (CMS-Phase2 upgrade)



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Actually in a *reduced format* for the future **Test Run** aimed at the validation of the experimental proposal:

- 25 cells in PbWO_4 ($22 \chi_0$)
- Surface $\sim 14 \times 14 \text{ cm}^2$
- Readout: **APDs** read by 2 **FEBs** connected to a **FC7 board**



Laser pulse system (at **450 nm**) for APD calibration

MC GENERATORS AND RECONSTRUCTION TOOLS

* Dedicated **MC generator** ([MESMER](#)) for main **background** and **elastic signal**:

- **Background** $\mu^+ N \rightarrow \mu^+ N l^+ l^-$ with $l = e, \mu \rightarrow \sigma_{bkg} \propto Z^2$

(G. Abbiendi, E. Budassi, C. M. Carloni Calame, A. Gurgone, F. Piccinini; [Phys. Lett. B 854 \(2024\) 138720](#))

- **Signal** $\mu^+ e^- \rightarrow \mu^+ e^- \rightarrow \sigma_{sig} \propto Z$

Developed at NNLO (Carloni Calame, C.M. *et al.*; [J. High Energ. Phys. 2020, 28](#))

* Detector description for **full simulation**: GEANT4;

* Tool for **offline reconstruction**: *FairMUonE* software ([FairRoot](#) frameworks based on [FairSoft](#) library)

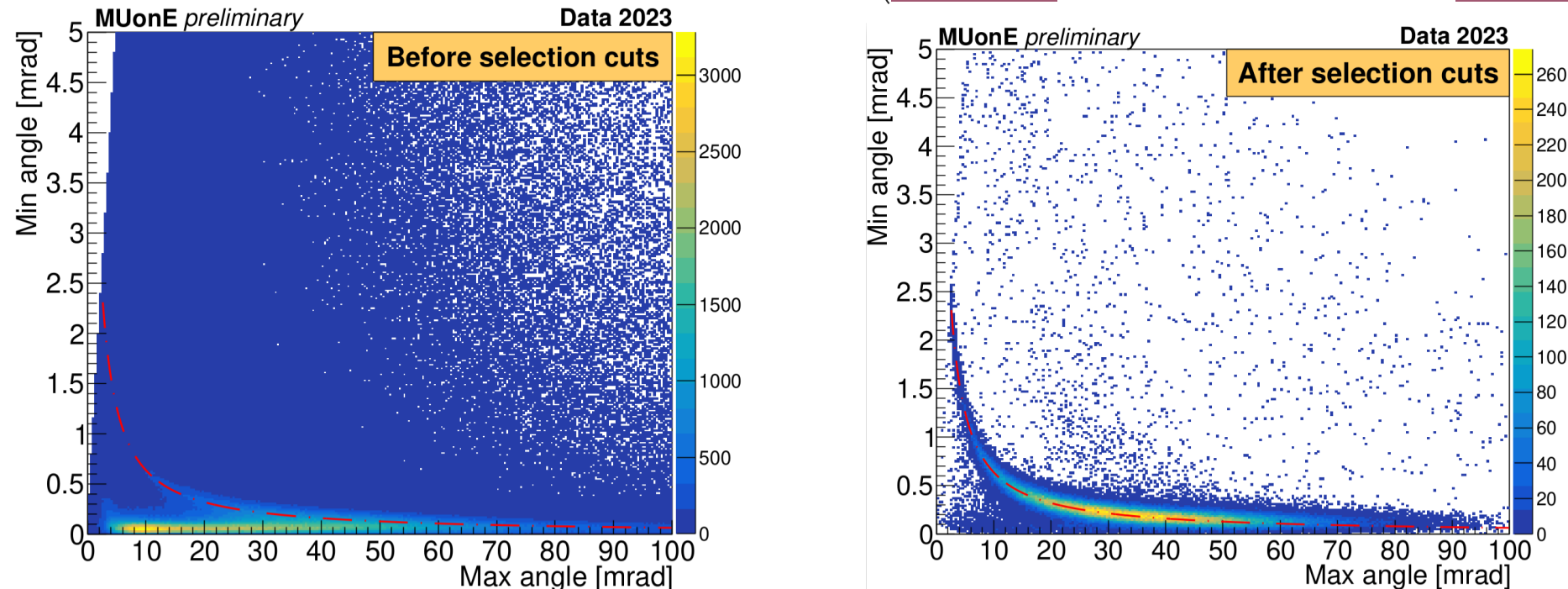


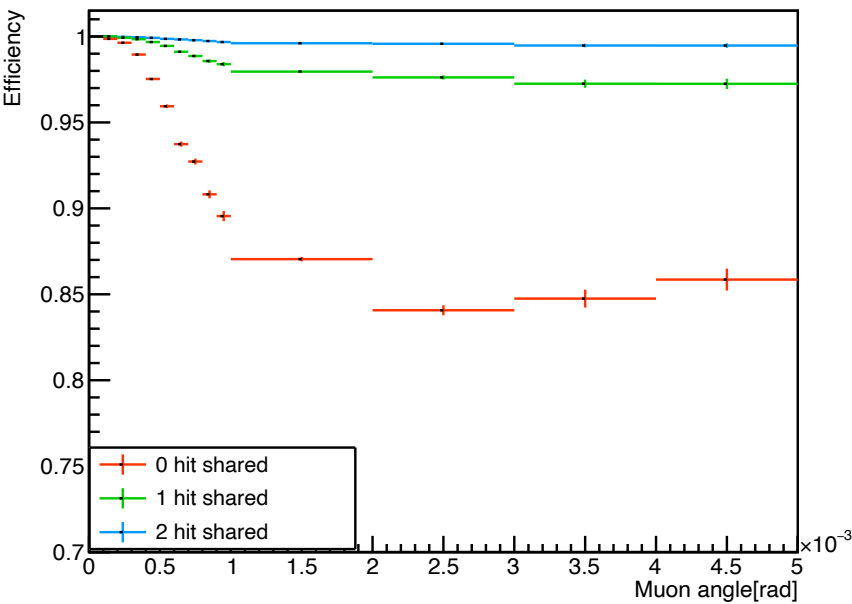
Figure: Skimmed events of a run *from Test Run 2023* (left), remaining reconstructed events after a **basic elastic selection** (right).

MC PERFORMANCE: EFFICIENCIES AND ANGULAR RESOLUTIONS

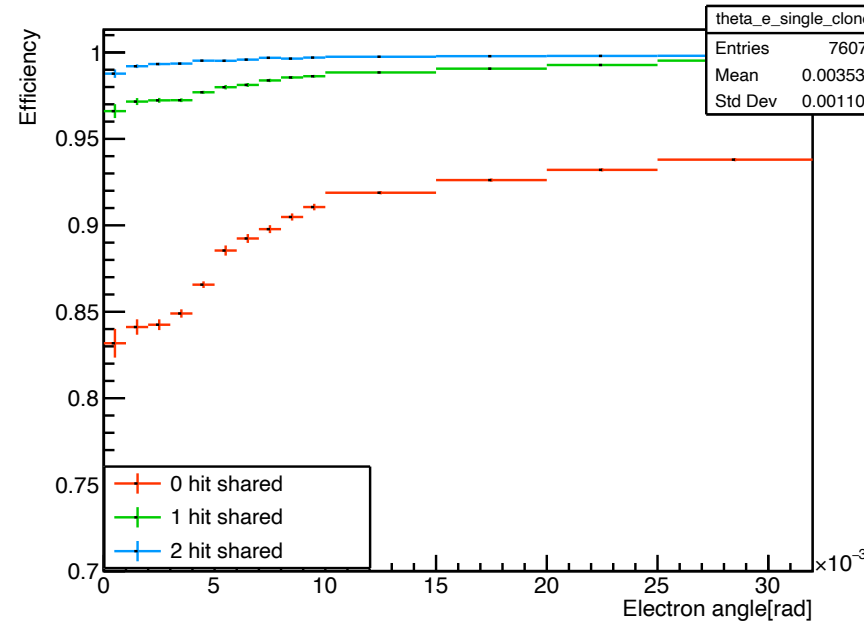
Tests on reconstruction algorithm:

- Single particles (μ, e^-) and elastic event reconstruction efficiencies with different reconstruction parameters (*# shared hits allowed between tracks*)

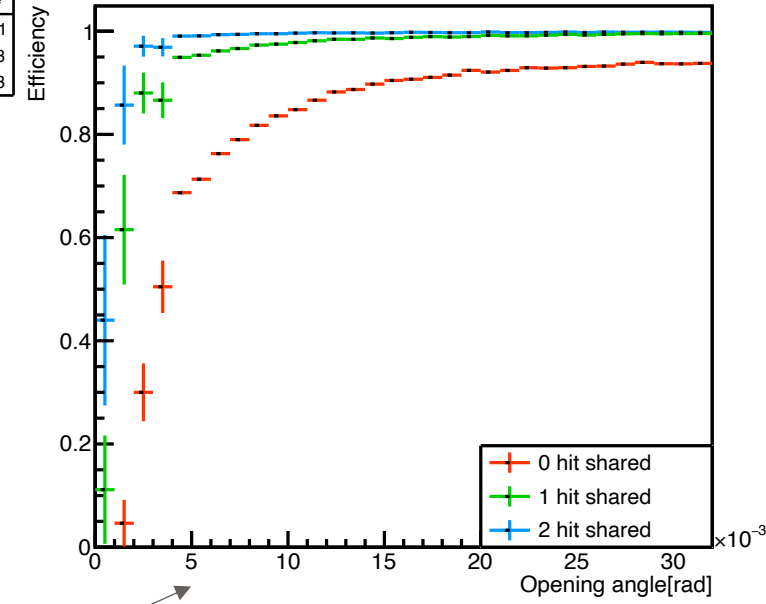
Single μ reconstruction efficiency



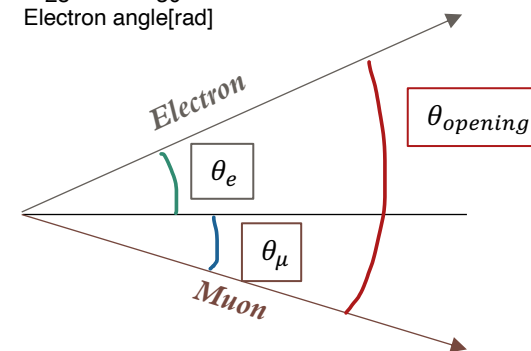
Single e^- reconstruction efficiency



$\mu + e^-$ reconstruction efficiency



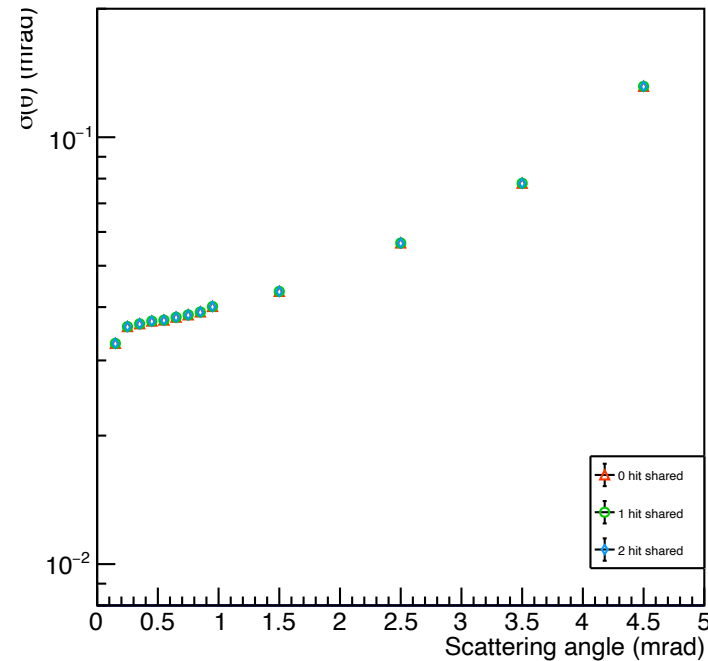
Flat and high efficiency for 2 shared hits



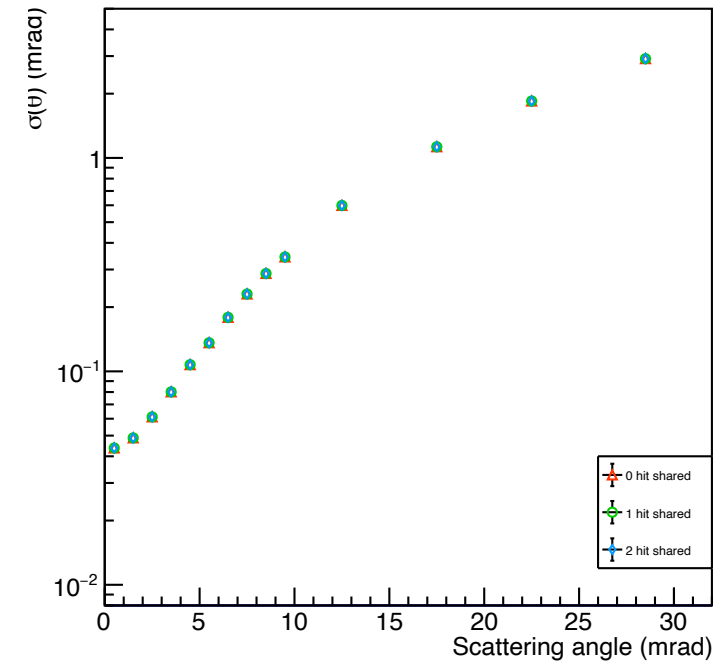
MC PERFORMANCE: EFFICIENCIES AND ANGULAR RESOLUTIONS

2. Angular resolution VS scattering angle (one of the most important feature for the experiment)

Muon angular resolution



Electron angular resolution



No degradation increasing the number of hit shared

Most important signal region:

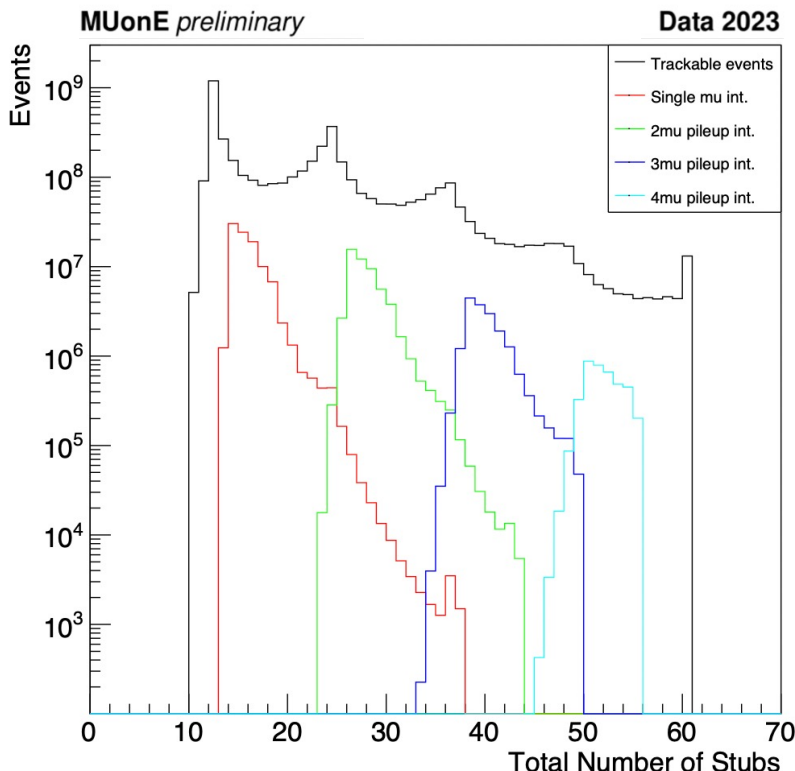
$$\theta_{\mu} > 1.5 \text{ mrad} : \sigma(\theta) \sim 40 - 100 \mu\text{rad}$$

$$\theta_e < 5 \text{ mrad} : \sigma(\theta) \sim 40 - 100 \mu\text{rad}$$

- 160 GeV muons of *M2 beam* line at CERN North Area;
- Max *asynchronous* rate at 50 MHz ($2 \times 10^8 \mu$ per spill);
- Setup: ECAL + 2 tracking stations;
- *Triggerless* DAQ \rightarrow Large data volumes processed offline.



Plan is to have data filter on FPGA; *now* an offline skimming algorithm has been implemented to preselect candidate events from target interaction: base on #hit in the two stations



On ~ 12 B merged events, the skimming procedure reduced the output at $\sim 1 - \text{few}\%$.

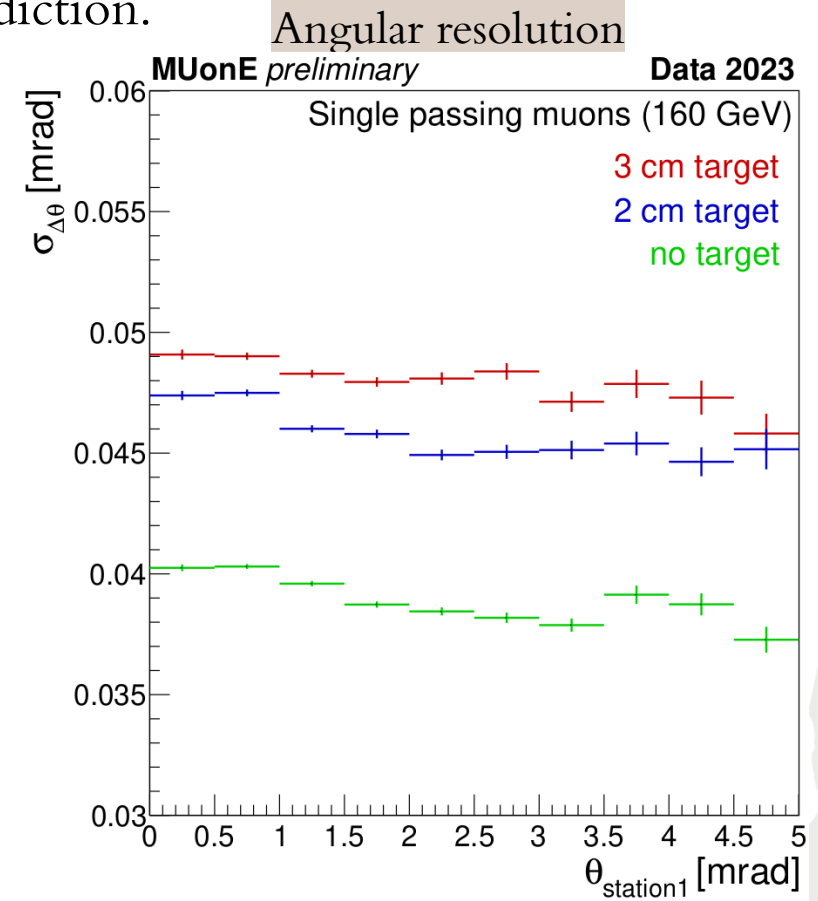
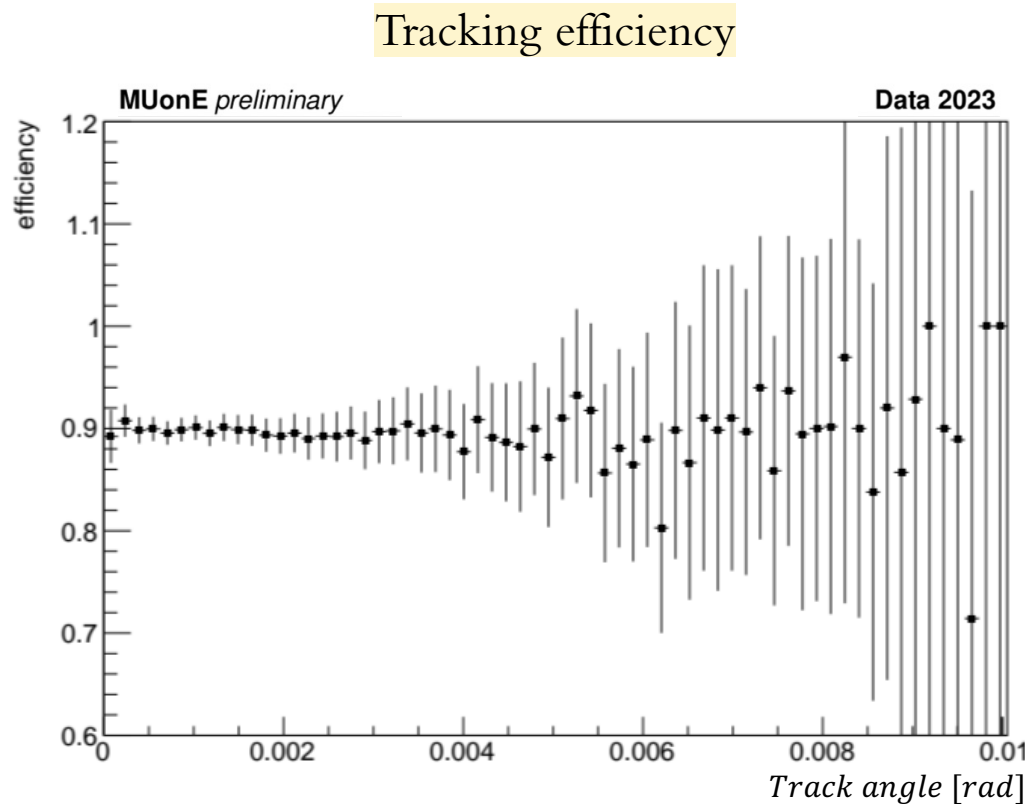
Different classes are well separated:

1. **Single** muon interactions
2. **2,3,4** pile-up muons with interactions

Figure: Fraction of different event multiplicities, in 2023 data, after skimming based on hits patterns.

RESULTS WITH DATA COLLECTED IN 2023

- Tracking efficiency as a function of selected golden muon's angle :
 - Average module efficiency $\sim 98\%$;
 - Given passing muons with 6 hits in first station, look for reconstructed muon in the second station.Result: flat efficiency at $\sim 90\%$ \rightarrow consistent with combinatorial result of individual module efficiency.
- Angular resolution as a function of selected golden muon's angle for different target sizes:
 - $\Delta\theta = \theta_{st1} - \theta_{st0}$ \rightarrow Sensitive to: intrinsic resolution, residual misalignment, **multiple scattering (MS)**
 - \rightarrow Estimate of **MS** consistent with calculation with PDG MS prediction.





CONCLUSIONS

- [Web site](#)
- *MUonE* proposes an *innovative and independent method* for the evaluation of the hadronic vacuum polarization term at LO α_{μ}^{HLO} which is *alternative* with the *previous ones*. Great possibility to *shade some light* on this intriguing *puzzle*!
 - Data analysis on **2023 Test Run data** is ongoing to determine *detectors performance* and *agreement* with *MC simulations*;
 - Next important steps:
 - **2024 October test run** to keep on validating the DAQ and synchronization of ECAL+tracker and validating the reconstruction and analysis tool;
 - **2025 Phase 1**: we presented a technical proposal to the SPSC in June for **4 weeks of running time** in 2025 to study the expected systematic errors and background under realistic conditions and make preliminary measurements of $\Delta\alpha_{had}(t)$.

Thank you for the attention!



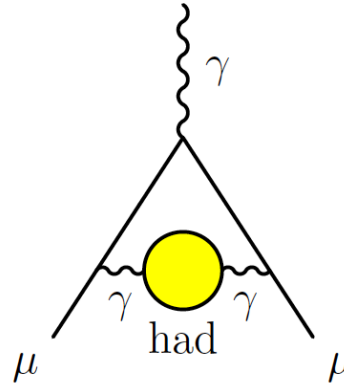
BACKUP

ANOMALOUS MAGNETIC MOMENT OF THE MUON

$$a_{\mu}^{SM} = \underbrace{a_{\mu}^{QED} + a_{\mu}^{EWK}}_{\text{Precise estimates from perturbation theory}} + a_{\mu}^{had}$$

Precise estimates from perturbation theory

a_{μ}^{HLO} + higher order terms



Hadronic contribution to the LO vacuum polarization term a_{μ}^{HLO} is not calculable through pQCD

Dominates theoretical uncertainty → 0.6%

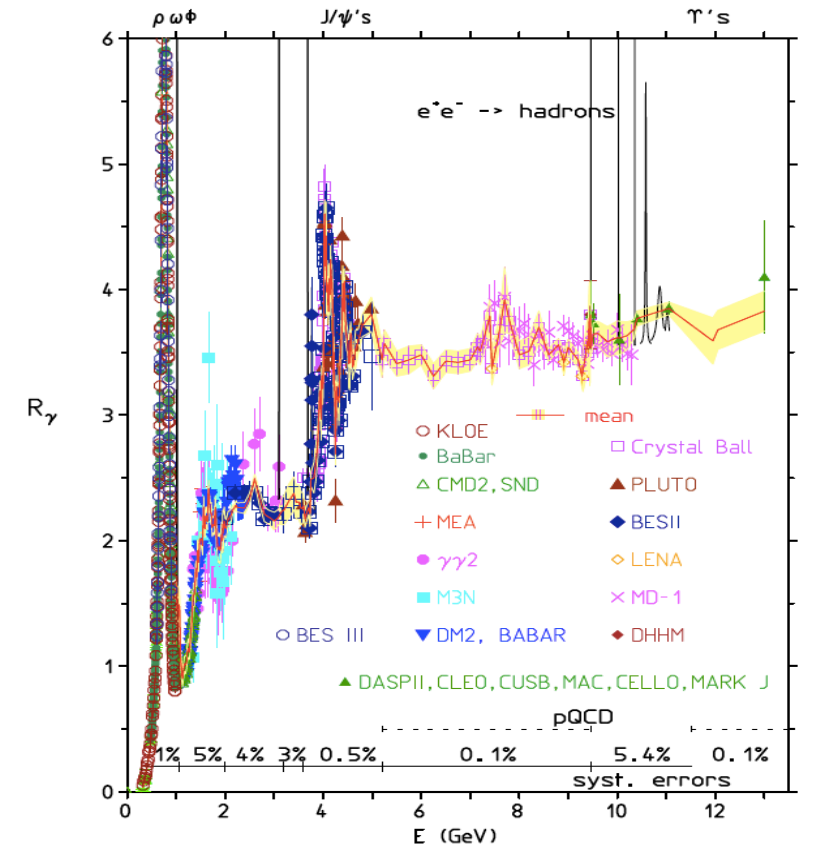
Reference approach (WP before BMW) is **data-driven**:

$$a_{\mu}^{HLO} = \left(\frac{\alpha m_{\mu}}{3\pi}\right)^2 \int_{4m_{\pi}^2}^{\infty} ds \frac{\hat{K}(s) R_{had}(s)}{s^2} \longrightarrow R_{had}(s) \propto \sigma(e^{-}e^{+} \rightarrow had) \text{ measurements}$$

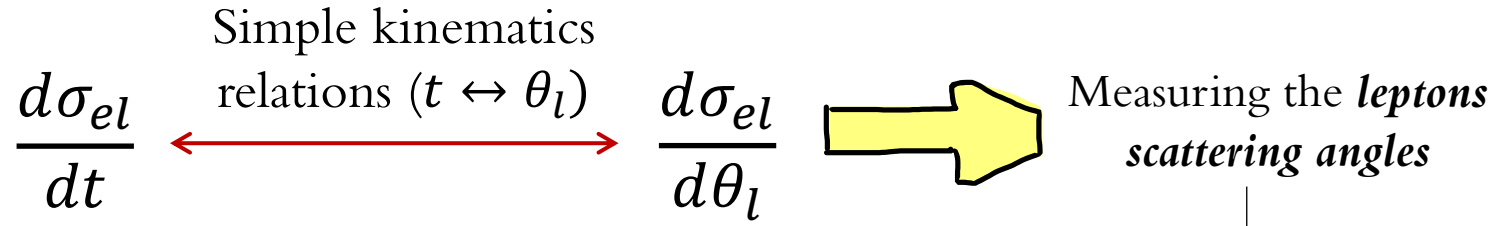
Alternative methods are needed!

Main contribution: region of *low energies*, highly *fluctuating* because of hadronic resonances and threshold effects

New a_{μ}^{HLO} with data from CMD-3 $\sigma(e^{-}e^{+} \rightarrow had)$ and with **LQCD (BMW)** weaken $\Delta a_{\mu}(th - exp)$ discrepancy, *introducing* some *tensions* with the reference theoretical estimate.



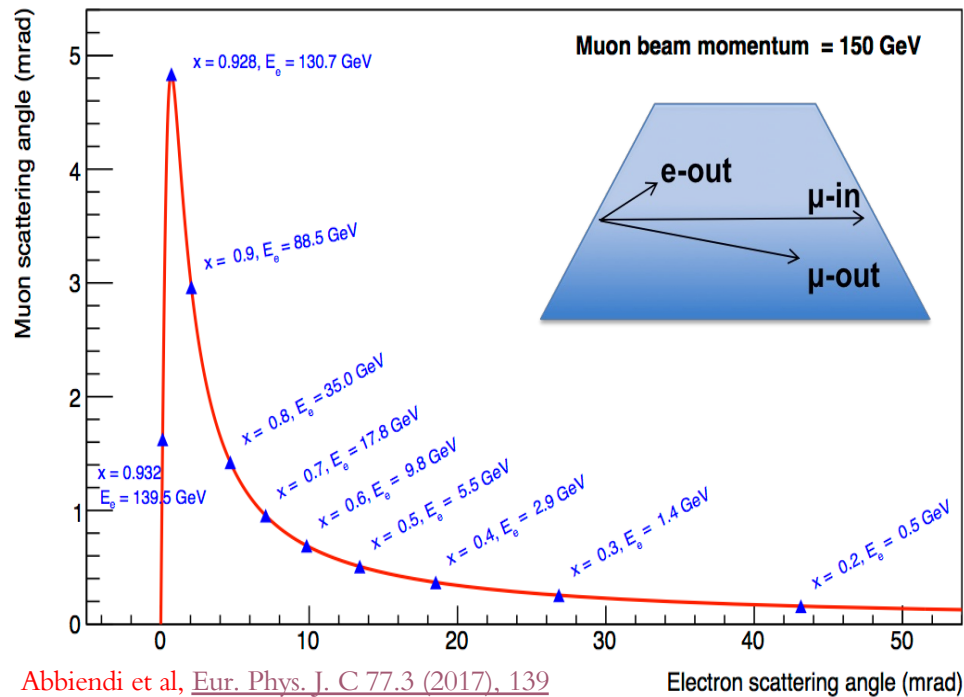
$\mu - e$ ELASTIC SCATTERING



$$0 < \theta_\mu < 5 \text{ mrad}$$

$$0 < \theta_e \lesssim 50 \text{ mrad}$$

ELASTIC CURVE



Abbiendi et al, *Eur. Phys. J. C* 77.3 (2017), 139

Helps in the selection of *purely elastic events*

Achievable precision

To be *competitive* with previous theoretical estimates:

precision on $a_{\mu}^{HLO} < 1\%$

40 stations
(tot: **60 cm** Beryllium) + 3 years of data taking with
an *integrated luminosity* of $1.5 \times 10^7 \text{ nb}^{-1}$ = Error statistical on
 $a_{\mu}^{HLO} < 0.5\%$



Main systematics effect:

1. Multiple *scattering*;
2. *Beam energy* knowledge (few MeV);
3. *Longitudinal* alignment;
4. Intrinsic *angular* resolution.

The challenge is to keep *precision* on *systematic effects* at the *same level*

Analysis: $\Delta\alpha_{had}$ parametrization and a_{μ}^{HLO} estimate

G. Abbiendi,
 Phys. Scr. 97 (2022) 054007;
[\[arXiv: 2201.13177\]](https://arxiv.org/abs/2201.13177)

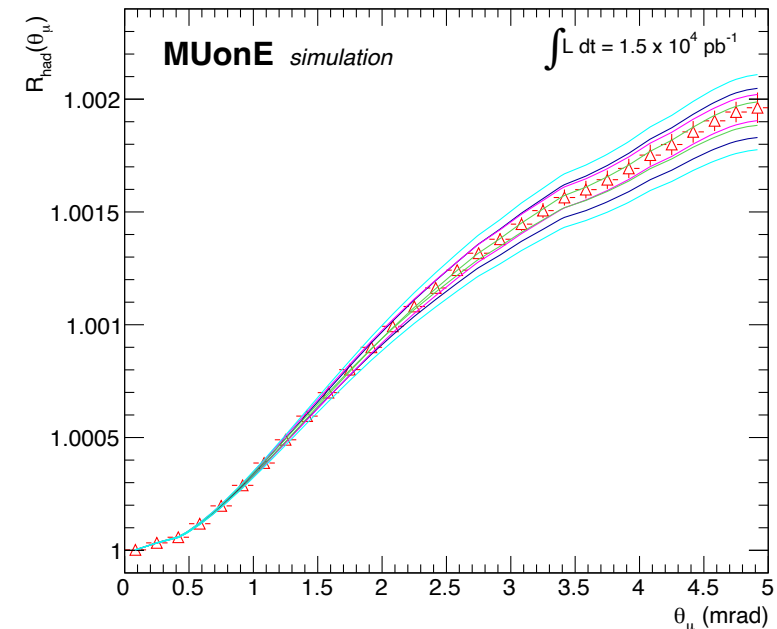
Inspired to the 1 loop QED calculation of the leptonic and $t\bar{t}$ pair vacuum polarization term

Parametrization with *two* variables K e M :

$$\Delta\alpha_{had}(t) = KM \left\{ -\frac{5}{9} - \frac{4M}{3t} + \left(\frac{4M^2}{3t^2} + \frac{M}{3t} - \frac{1}{6} \right) \frac{2}{\sqrt{1 - \frac{4M}{t}}} \ln \left| \frac{1 - \sqrt{1 - \frac{4M}{t}}}{1 + \sqrt{1 - \frac{4M}{t}}} \right| \right\}$$

1. **Template fit**: generation of a grid of points in the parameters space (K, M) ;
2. R_{had} distribution as a function of the leptons scattering angle *for different templates*;
3. χ^2 of the **data/pseudo-data** and **templates**.

$$R_{had} = \frac{d\sigma(\Delta\alpha_{had})}{d\sigma(\Delta\alpha_{had} = 0)}$$



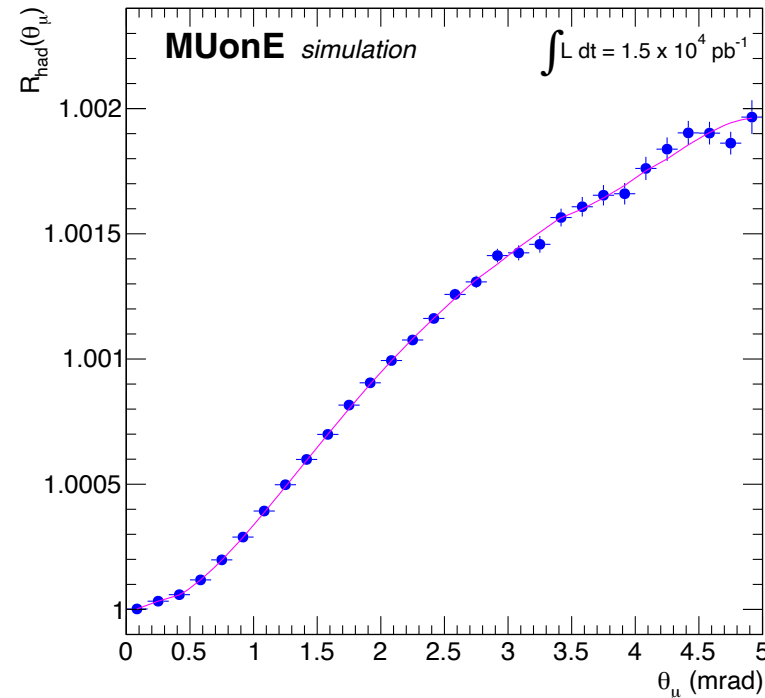
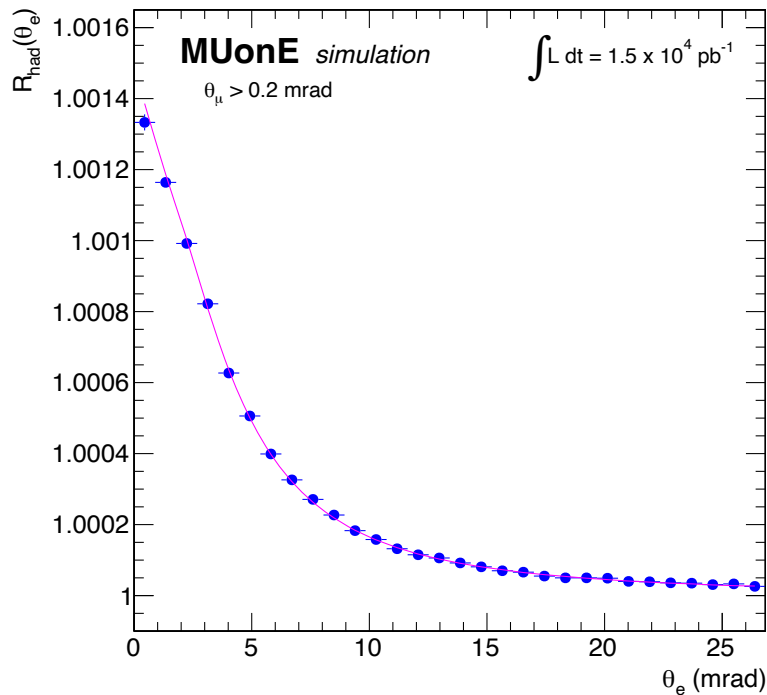
Analysis: $\Delta\alpha_{had}$ parametrization and a_{μ}^{HLO} estimation

$\Delta\alpha_{had}$ extraction in the final experiment
 computed using 2D (θ_{μ}, θ_e)



The value would be inserted in the *master integral* for a_{μ}^{HLO}

Example of a pseudo-experiment:



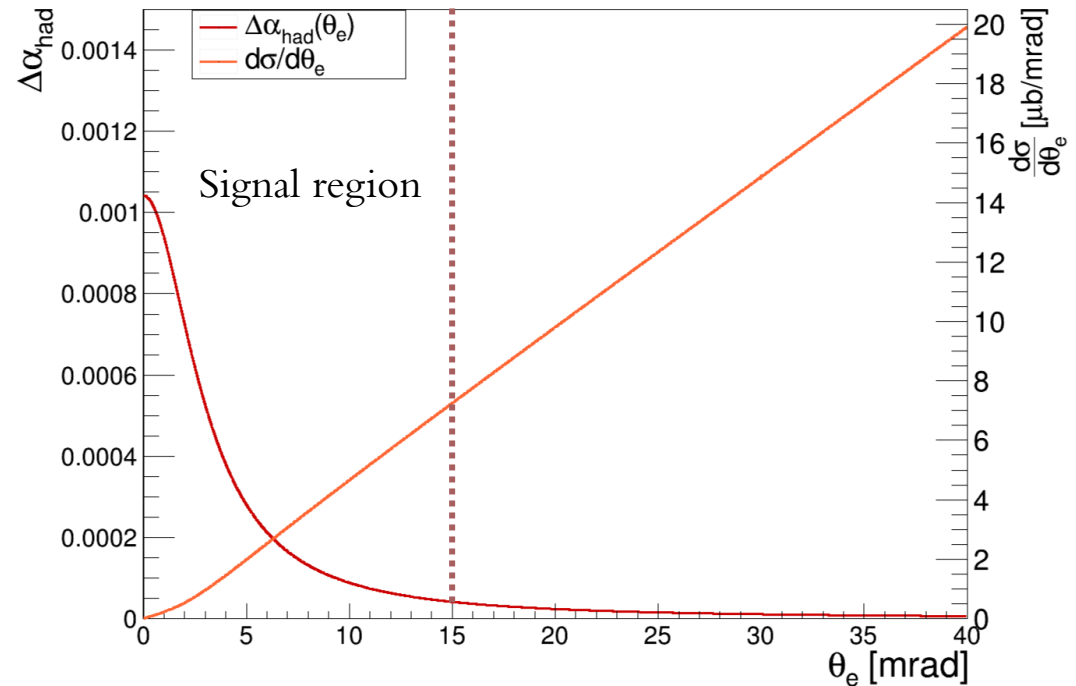
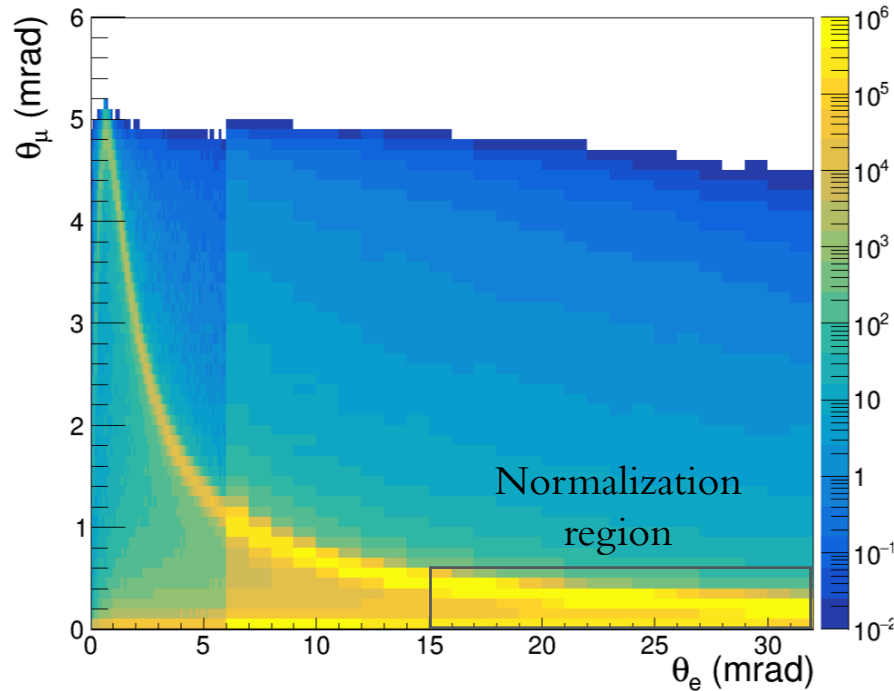
Simulation result:

$$a_{\mu}^{HLO} = (688.8 \pm 2.4) \times 10^{-10}$$

Input value for generation:

$$a_{\mu}^{HLO} = 688.6 \times 10^{-10}$$

Strategy for systematic effects

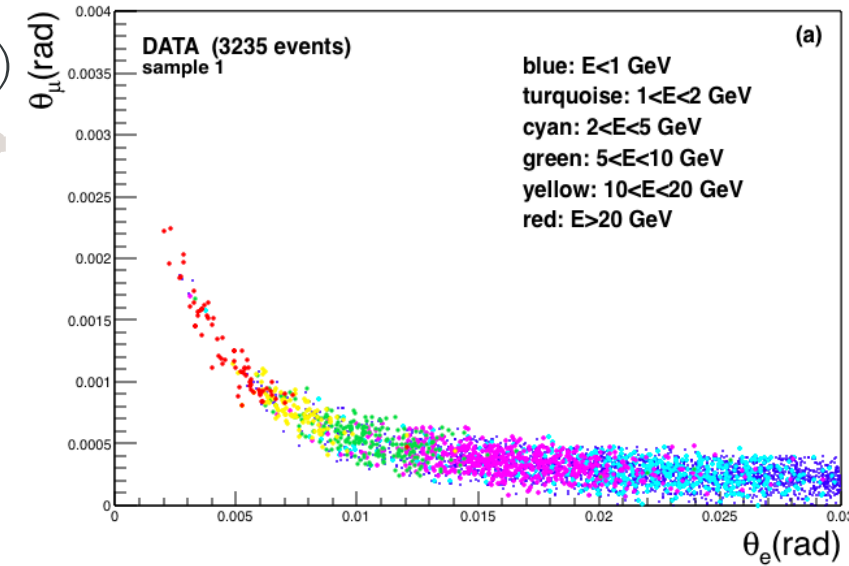


- 1) *Larger systematic effects* (intrinsic angular resolution, beam energy): use **normalization region** -many events there- to *calibrate* them;
- 2) *Other systematics*: included as **nuisance parameters** in a *combined fit with signal* (CMS Combine tool).

TESTS SINCE 2018

(TB: test beam, TR: test run)

MUonE collaboration, [JINST 16 \(2021\) P06005](#)



- TB 2017-2018 → Multiple scattering analysis (MUonE collaboration, [arXiv:1905.11677](#)) and first selection of elastic events (MUonE collaboration, [JINST 16 \(2021\) P06005](#));
- **Tracker** TB October–November 2021 → demonstrate *that the entire DAQ chain works properly* with asynchronous muon beam;
- **Calorimeter** TB July 2022, June–July 2023, July 2024 → Detect, amplify end read signals + calibration of APDs;
- TB October 2022 → **ECAL+Tracker (1 station)** : Test all the chain with a partial setup;
- TR August–September 2023 → **ECAL+Tracker (2 stations)**: Synchronization of the detectors and collect good statistics for data analysis (see poster by [R.Pilato](#)).

Foreseen tests:

- TR 2024: → ECAL+Tracker (2 station)
- Sent proposal for phase 1 of the experiment to the SPSC in 2025 with a small scale setup: **3 stations + ECAL+muon filter+BMS**. Expected to collect data to do the measurement with a 20% statistical uncertainty.